A NUMI Wide-Band Beam Shield Design That Meets The Concentration Model Ground Water Criteria

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Introduction

This note describes a NUMI wide-band beam line shield design that is adequate for 3.7×10^{20} 120 GeV targeted protons per year. The adequacy of the design is determined from CASIM results that satisfy the standard Fermilab Concentration Model ground water criteria as described in [1, 2] with no credit taken for any reduction in the calculated initial concentration due to mixing, dispersion, or radioactive decay. It assumes the three-horn design of Malensek, et al. commonly referred to as H6.6. The beam line is assumed to be centered in a cylindrical tunnel that is 6.6 meters in diameter located entirely in dolomite.

Review of the Concentration Model

The Concentration Model [1, 2] was developed principally to apply to the case of a near-surface Fermilab target station located in the glacial till several meters above a ground water aquifer. The model conservatively assumes that radioactivity builds up to its saturation value in the soil surrounding a target station or beam dump without any removal due to flowing water. After the buildup to saturation levels, water is assumed to pass through the soil and leach out the radioactivity. In this model, the concentration C_i, (in pCi per ml-yr) for radionuclide i in water close to the target station or dump is given by

$$C_i = \frac{N_p \cdot S_{\max} \cdot 0.019 \cdot K_i \cdot L_i}{1.17\times10^6 \cdot \rho \cdot w_i} \qquad \text{(eq. 1)}$$

where

N_p is the number of incident protons per year

$S_{\max}$ is the maximum star density (in stars/cm^3) per incident proton in the unprotected soil or rock obtained from a CASIM calculation.

K_i is the radionuclide production probability per star (0.075 atoms / star for ^{3}H , 0.02 atoms / star for ^{22}Na in soil; 0.03 atoms / star for ^{3}H, 0.02 atoms / star for ^{22}Na in dolomite)

L_i is the leachability factor for the radionuclide (0.9 for ^{3}H and 0.135 for ^{22}Na in soil; 0.9 for ^{3}H and 0.009 for ^{22}Na in dolomite.)

ρ is the material density (2.25 gm / cm^3 for moist soil, 2.8 gm / cm^3 for dolomite)

w_i is the weight of water divided by the weight of soil needed to leach 90% of the *leachable* radioactivity that is present (0.27 for ^{3}H and 0.52 for ^{22}Na).

The factor 0.019 relates the *maximum* star density in the unprotected soil region surrounding a typical beam dump to the *average* star density within a volume that contains about 93% of the radioactivity produced in the unprotected region. The factor 1.17x10^6 converts the result to the desired units. (See the appendix for a discussion of the factor 0.019 and possible modifications to it for the NUMI tunnel geometry.)

The final concentration in ground water, C_f, for a particular radionuclide is related to the initial concentration by

$$C_f = C_i \cdot R_{till} \cdot R_{mix} \cdot R_{dolomite}$$

where R_{till} is a reduction factor in the model that takes account of the migration of radionuclide downward through the soil (glacial till) to an underlying aquifer and includes dispersion and radioactive decay *en route*. R_{mix} is a reduction factor that takes into account concentration reduction due to mixing in the transition region at the aquifer boundary where the flow changes from vertical to horizontal, and $R_{dolomite}$ is a reduction factor that takes into account dispersion and radioactive decay in the horizontal flow of the aquifer *en route* to some distant location, e.g. the site boundary or the nearest drinking water well. A schematic illustration of the model is shown in Fig 1.

Knowledge of soil constituents, possible activation products, and leaching analyses of activated soil samples has shown that the only two radionuclides that require consideration are ^{3}H and ^{22}Na (see [1] and references therein). The regulatory limit on the final concentrations that must be met for these two isotopes then can be expressed as

$$\frac{C_f\left({}^{3}H\right)}{C_{reg}\left({}^{3}H\right)}+\frac{C_f\left({}^{22}Na\right)}{C_{reg}\left({}^{22}Na\right)}\leq 1 \qquad \text{(eq. 2)}$$

where $C_{reg}\left({}^{A}Z\right)$ is the regulatory limit on the concentration for isotope ${}^{A}Z$. These limits are 20 pCi per ml for ${}^{3}H$ and 0.4 pCi per ml for ${}^{22}Na$ in ground water. [3, 4]

The NUMI design locates the target station and decay region in dolomite bedrock below the region of glacial till. Thus no credit can be taken for concentration reduction due to vertical migration through the till or for mixing at the till-dolomite interface. Therefore R_{till} and R_{mix} must be set equal to 1. In addition, Fermilab made a decision that no credit should be taken for possible concentration reduction arising from flow within the dolomite aquifer in the "standard" application of the Concentration Model [2]. This decision arose from concerns related to State of Illinois regulatory requirements for resource ground waters [5][1]. Thus $R_{dolomite}$ also should be set equal to 1 and therefore C_f becomes equal to C_i. As is the case for glacial till, there are only two principal radionuclides whose production and leachability needs to be considered in dolomite. These are ${}^{3}H$ and ${}^{22}Na$.

Limiting Star Density

Equations 1 and 2 , together with the material- and radionuclide-dependent factors given in the previous section, can be combined to derive a limit on the maximum star density permitted in the dolomite surrounding the NUMI tunnel for a given number of protons targeted per year. This limit can be expressed as

$$N_p \cdot S_{\max} \leq \left[\frac{0.019}{1.17\times10^{6}\cdot 2.8}\cdot\left\{\left.\frac{0.03\cdot 0.9}{0.27\cdot 20.}\right|_{{}^{3}H}+\left.\frac{0.02\cdot 0.009}{0.52\cdot 0.4}\right|_{{}^{22}Na}\right\}\right]^{-1}$$

which gives

$$N_p \cdot S_{\max} \leq 2.94\times10^{10}\left(stars - cm^{-3} - yr^{-1}\right)$$

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[1] 35 IAC 620, Section 620.301(a) states that "No person shall cause, threaten or allow the release of any contaminant to a resource ground water such that: 1) Treatment or additional treatment is necessary to continue an existing use or to assure a potential use of such ground water; or 2) An existing or potential use of such ground water is precluded.

For 3.7x10^{20} protons per year, the upper limit on the star density is 7.9x10^{-11}stars cm^{-3} proton^{-1}. (See the Appendix, however, for a discussion of reasons why the upper limit on the star density should possibly be smaller.)

Description of CASIM Geometry

The Wide-Band Beam shielding geometry that was modeled is illustrated in Figure 2. The target consisted of eight identical graphite segments, each 12.5 cm long, 2 mm in radius, separated by 8 cm and surrounded by air. The target was followed by three magnetic horns composed of aluminum conductors, also surrounded and filled with air. The horns' inner conductor dimensions followed the H6.6 design of Malensek, et al. The outer radius (limit) for each horn's magnetic field was 25 cm. The magnetic field strength between the inner and outer conductors was assumed to be

$$\left|\vec{B}\right| = \frac{34kG - cm}{r(cm)}$$

which corresponded to an operating current of 170 kamps.

The target hall region, defined as the first 50 meters of the tunnel, contained varying amounts of steel shielding around the beam line. Steel annuli 145 cm thick (30 cm < r < 175 cm) surrounded the region containing the target and first two horns. The third horn was surrounded by a 170 cm thick steel annulus (30 cm < r < 200 cm).

The rather long drift space between the second and third horns also required shielding. It was modeled as two separate regions. The upstream region contained a steel annulus 95 cm thick (75 cm < r < 170 cm) and the downstream region contained a steel annulus 70 cm thick (100 cm < r < 170 cm). Helium gas filled the region between the second and third horns out to a radius of 75 cm from the beam centerline with the remaining space filled with air.

The evacuated decay pipe was modeled as a steel tube 100 cm in radius and 2 cm in wall thickness. The pipe was surrounded by an annulus of concrete 130 cm thick (102 cm < r < 232 cm). The 3.3 meter radius decay tunnel ended in a 500 cm long, 200 cm radius steel beam dump surrounded by concrete.[2]

CASIM Results

Two CASIM runs were done, each with 10^6 incident particles, to determine the star density distribution in the dolomite surrounding the tunnel. The first run focused on the first 50 meters of the tunnel that contains the target station. The second run covered the full 800 meter length of the decay tunnel.

The results for the target station region are shown in Figure 3. The calculated star densities for the innermost radial bins of the tunnel wall (330 cm < r < 340 cm) are plotted as a function of the longitudinal position along the tunnel. The radial bin size was $\Delta r = 10$ cm. The longitudinal bin size was Δz=100 cm. The results are compared to the permitted upper limit of 7.9×10^{-11} stars cm^{-3} $proton^{-1}$ discussed above. Within the errors, the calculated results satisfy this limit over the target hall region. In the region 1500 cm < z < 2500 cm the star density is about a factor of 2 below the limit. It might be possible to further refine the design by increasing the inner radius of the steel to 85 cm in this region without exceeding the ground water limit.

The results for the full 800 meter length of the decay tunnel are shown in Figure 4. This plot is similar to Figure 3 except that the longitudinal bin size has been increased to Δz=1600 cm. The results are also compared to the permitted upper limit of 7.9×10^{-11} stars cm^{-3} $proton^{-1}$. Within the errors, the calculated results satisfy the limit over the length of the decay tunnel, with the possible exception of a very limited region for 220 meters < z < 280 meters where the results may slightly exceed the limit.

Discussion of Results

Target Station Region

There is a line-of-sight from the target that is defined by the edge of the 30 cm radius hole in the steel shielding downstream of the second horn. This line-of-sight begins to intersect the inner surface of the shielding between horns 2 and 3 if its inner radius is less than about 96 cm. It was found that if the radial thickness of the shield was held

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[2] Details of the beam dump design at the end of the decay tunnel were not addressed by these calculations. While the modeled steel dump dimensions are roughly consistent with what is necessary, they are not meant to represent a final dump design. The final design will also have to comply with the regulatory limits.

constant but its inner radius was reduced much below 100 cm, then the star density in the surrounding dolomite increased and could exceed the ground water limit for a range in z that depended on how much smaller the inner radius became. This then required an increase in the outer radius of the shielding to compensate. Conversely, increasing the inner radius from 75 to 100 cm for 2500 cm < z < 4260 cm resulted in a reduction of the star density to acceptable levels, presumably because secondary particles from the target region could no longer directly strike the inner surface of the shield.

The shield surrounding the third horn (4260 cm < z < 4600 cm) was found to require somewhat more steel radially, compared to the shielding around the target and first two horns. This is probably due to the spread of neutral secondaries and mis-focused charged secondaries that can strike the upstream face of the steel surrounding the third horn out to a distance about 100 cm. This would reduce the effective radial thickness of that shielding, essentially because there is a larger secondary beam "spot" striking the upstream face of that shield. To some extent there must be a correlation between a decrease of the inner radius of the shield upstream of the third horn and the necessary outer radius of the shield surrounding the third horn, since particles from the target region that would have struck the upstream face of the shield around the third horn would begin to interact in the more upstream shielding if its radius was much below 100 cm. It may be possible to reduce the overall amount of steel required somewhat with further calculations, although it is unlikely that it will be a significant reduction. The amount of steel shielding contained in the modeled target hall region is 3410 tons.

The steel shielding downstream of the third horn was modeled to extend all the way to the upstream end of the decay pipe and surrounding concrete shield. There was no gap to permit access to the decay pipe vacuum window. Earlier calculations with about a 2 meter gap led to star densities in the dolomite that exceeded the ground water limit, but this was only over a limited range of z that was roughly the length of the gap.

Decay Pipe Region

The decay pipe results (figure 4) show a region for 220 m < z < 280 m where the star density may slightly exceed the ground water limit, preceded by a decrease in the star density for 100 meters < z < 200 meters. The rise in star density that begins at about 160 meters is consistent with the fact that the line of-sight from the target through the edge of the 30 cm hole after the third horn begins to strike the decay pipe wall near this location in z. The dip and rise for $80 \text{ m} < z < 250 \text{ m}$ is characteristic of the effect of collimators seen in earlier calculations. To reduce the maximum star density in the $220 \text{ m} < z < 280 \text{ m}$ region to the desired limit would require no more than about 5 cm of additional concrete. However, given the systematic uncertainties typically associated with CASIM calculations (roughly a factor of 2) as well as the statistical uncertainties, no attempt was made to refine the geometry further and repeat the calculation. The volume of concrete for the shielding surrounding the decay pipe is 1.02×10^{10} cm^3 or 13,340 yds^3.

Note that the shielding configuration described here assumed cylindrical symmetry about the beam center line for all components. Thus, the radial shield thicknesses given in this note represent the minimum thicknesses necessary. Most practical shielding designs are not cylindrically symmetric and therefore would require a greater volume of material. In addition, some further modifications to the shield thickness might be required if the beam center line is not centered in the tunnel.

REFERENCES

1. A. J. Malensek, et al., "Ground Water Migration of Radionuclides at Fermilab", Fermilab TM-1851, August 1993, and references therein.

2. J. D. Cossairt, "Use of a Concentration-based Model for Calculating the Radioactivation of Soil and Ground water at Fermilab", Fermilab Environmental Protection Note No. 8, December 1, 1994 .

3. US EPA regulations 40 CFR Part 141.

4. "Radiation Protection of the Public and the Environment', DOE Order 5400.5, 1990.

5. "Ground Water Quality Standards", 35 Illinois Administrative Code 620, November 7, 1991.

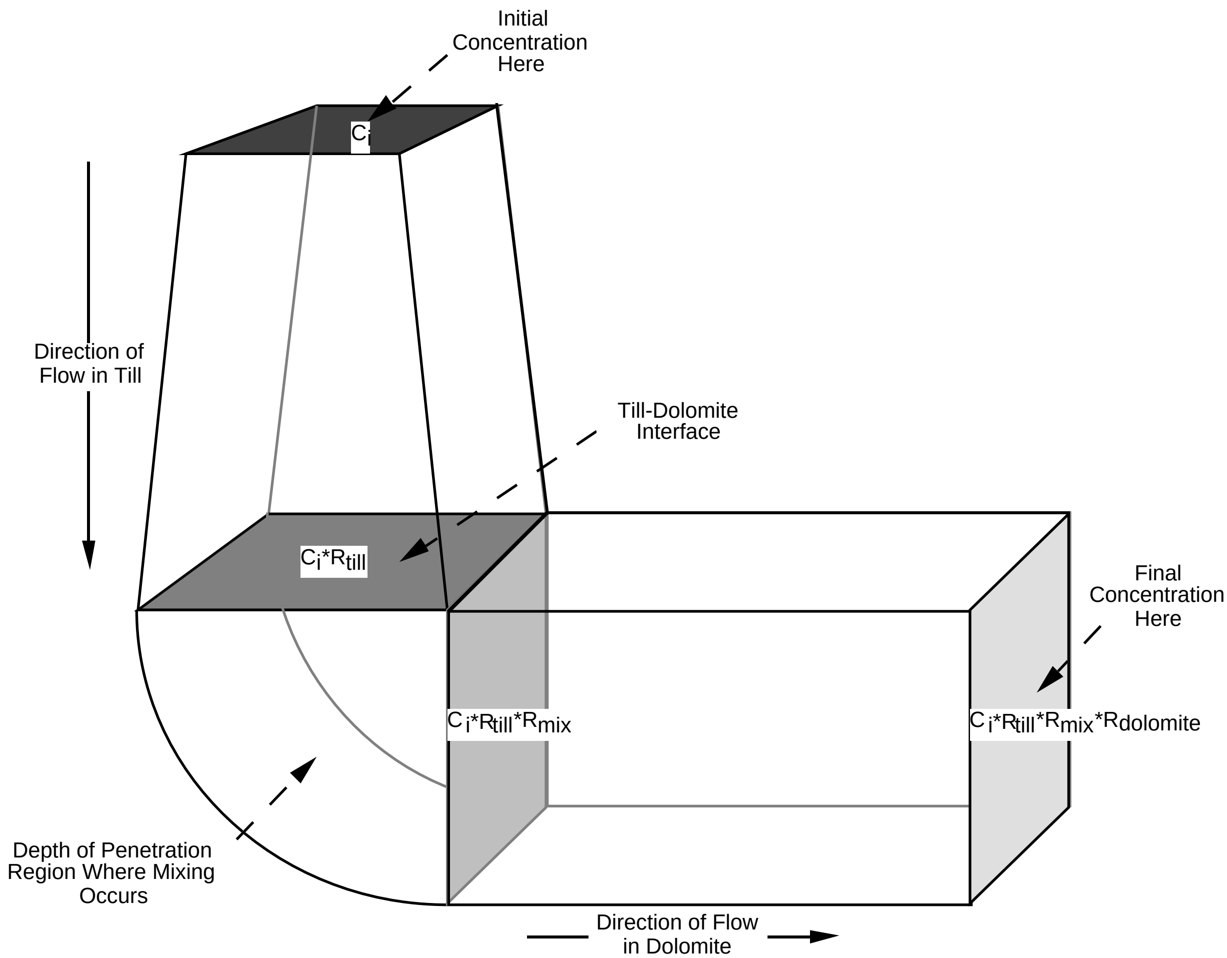

Figure 1 - Schematic illustration of the Concentration Model

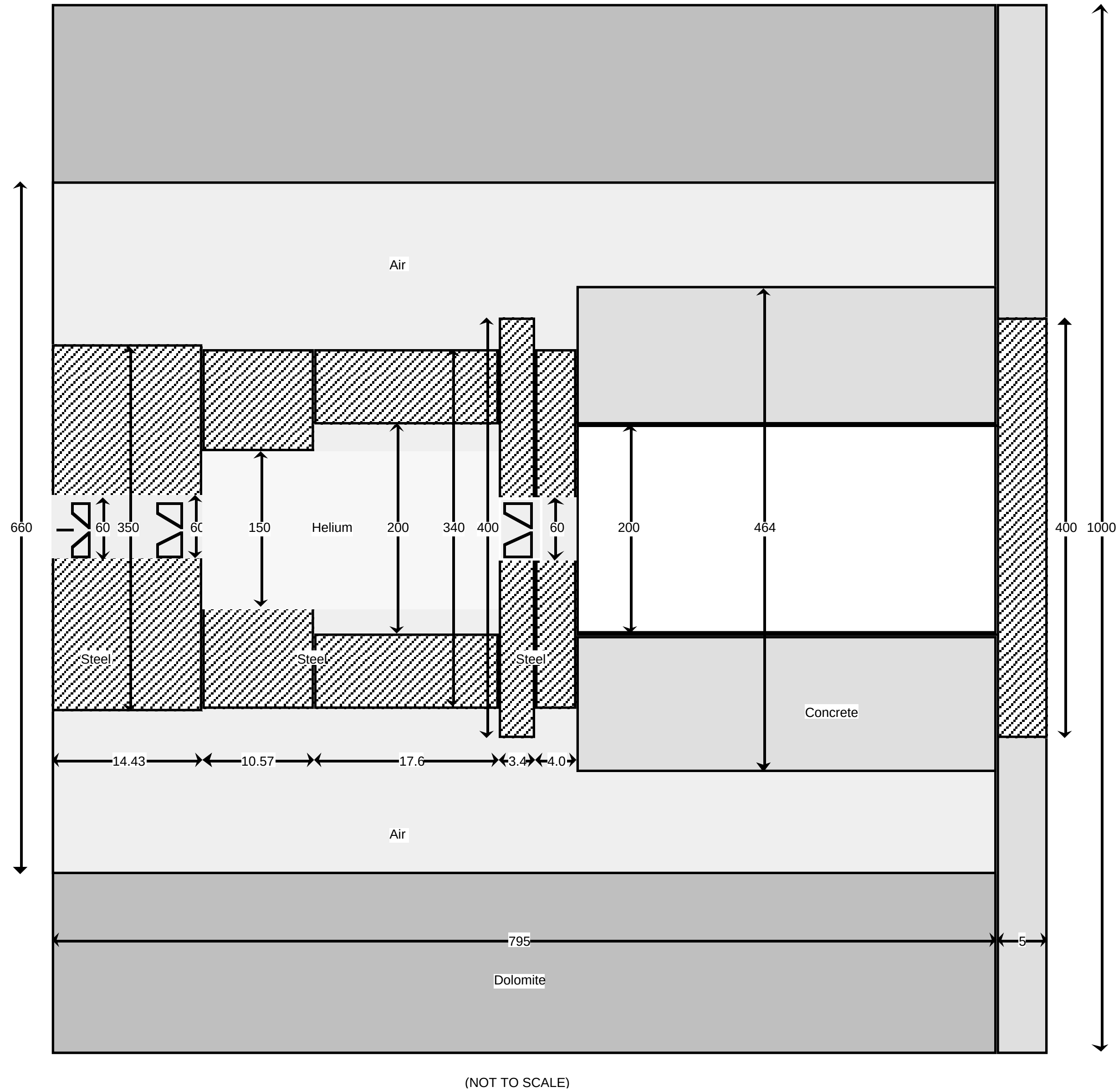

Figure 2 - NUMI tunnel and shielding geometry used for CASIM calculations. The drawing is not to scale. The units of the dimensions in the longitudinal direction are given in meters; the units in the radial direction are given in cm.

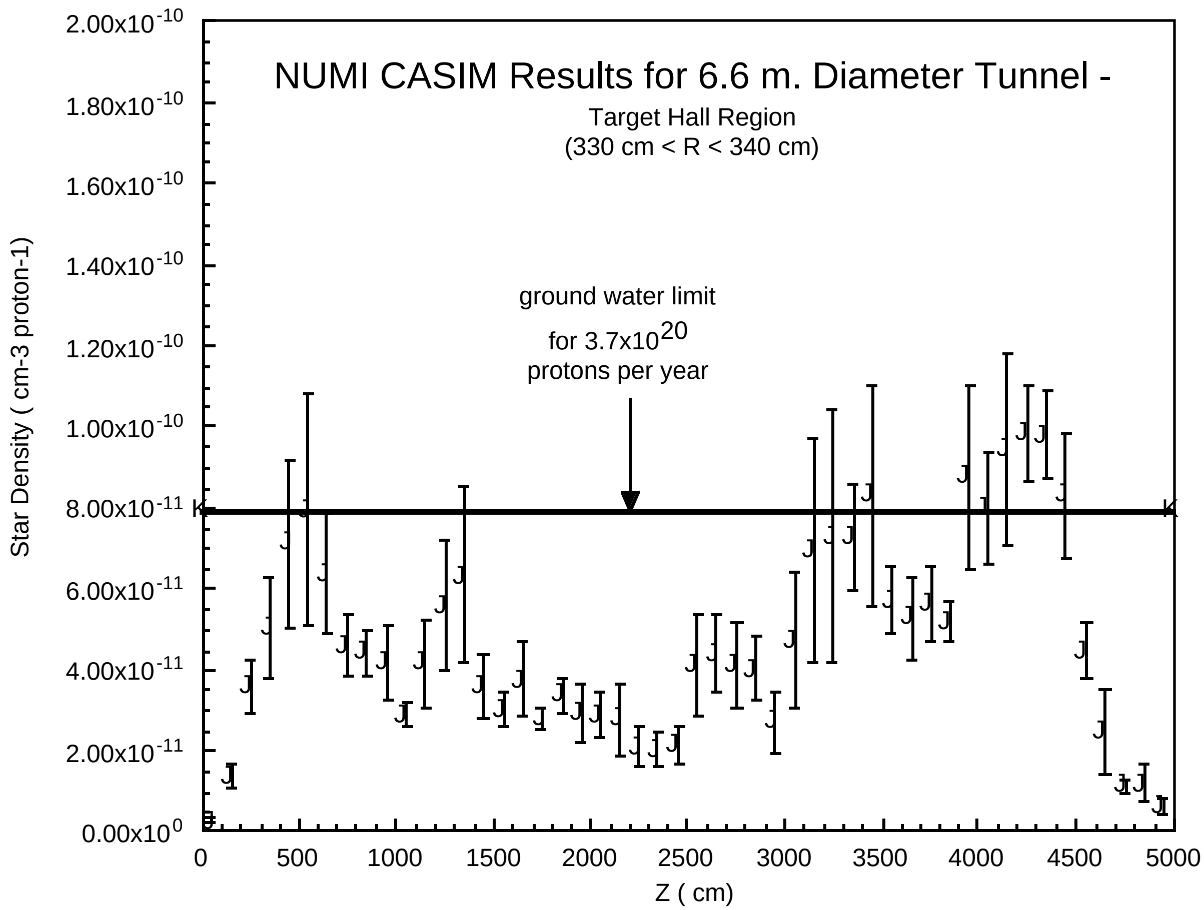

Figure 3 - CASIM results for the target hall region (z <50 meters). Results are plotted for the innermost radial bin in the dolomite (330 cm < r < 340 cm). Longitudinal bin size is Δz=100 cm. The solid line at 7.9×10^{11} stars cm^{-3} proton^{-1} corresponds to the ground water limit discussed in the text.

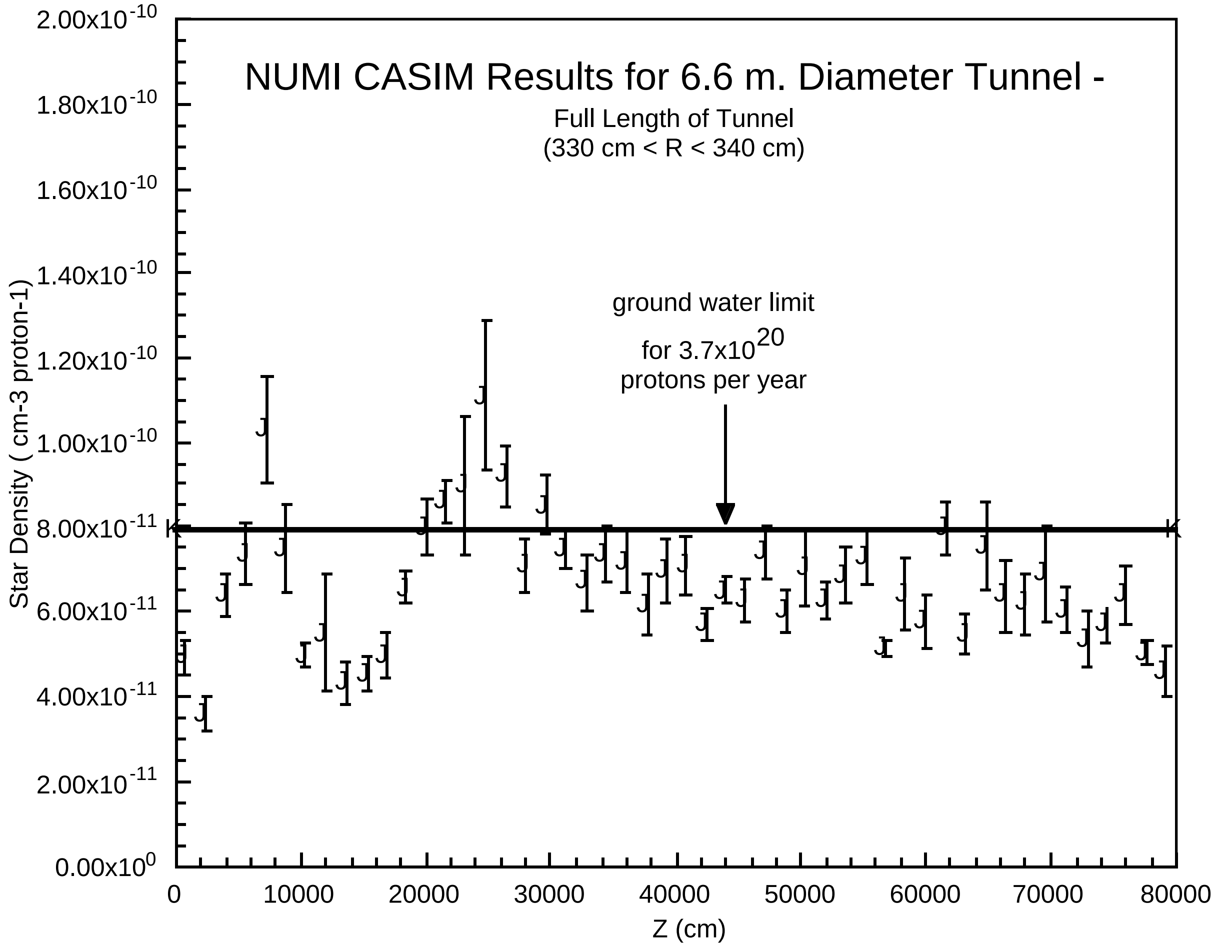

Figure 4 - CASIM results over the full 800 meter decay tunnel. Results are plotted for the innermost radial bin in the dolomite (330 cm < r < 340 cm). The longitudinal bin size is Δz=1600 cm. The solid line at 7.9×10^{11} stars cm^{-3} proton^{-1} corresponds to the ground water limit discussed in the text.

Appendix

Averaging of the Star Density Distribution

Review of the Standard Concentration Model

The standard expression for the concentration of a radionuclide in groundwater from [1] includes the term 0.019 * $S_{max.}$ This term represents the *average* star density found in the unprotected soil region outside a typical beam dump under certain assumptions. The first assumption is that the star density in the soil decreases exponentially with the radial distance from the beam centerline. The second assumption is that it also decreases exponentially with the distance along the beam direction, after the point at which the hadronic shower has reached its maximum. The third assumption is that it is reasonable to average the star density over a volume defined by the values in R and Z at which the star density has dropped to 1% of its maximum value and use this average to compute the radionuclide concentrations.

For the beam dump case discussed in [1] the star densities in soil were assumed to vary as

$$r(R) \propto e^{-2.5 \bullet R(meters)}$$
$$z(Z) \propto e^{-1.0 \bullet Z(meters)}$$

The characteristic distances over which the star density decreases in R and Z are different, decreasing faster in R that in Z. The values in soil at which r(R) and z(Z) decrease to 1% of their maximum values from [1] are 1.84 meters and 4.6 meters, respectively, for the standard beam dump geometry. The average star density is then

$$S_{avg} = S_{\max} \cdot \frac{\int_0^{1,84} e^{-2.5R} RdR}{\int_0^{1.84} RdR} \cdot \frac{\int_0^{4.6} e^{-1.0Z} dZ}{\int_0^{4.6} dZ} \qquad \text{or}$$

$$S_{avg} = S_{\max}(0.089)(0.215) = 0.019 \cdot S_{\max}$$

Modifications to the Averaging Procedure

Some modifications to this averaging procedure are necessary for the NUMI tunnel geometry, which is not similar to the more compact beam dump geometry. A more general expression for the average star density, S_{avg} , in some region (assuming cylindrical symmetry about the beam direction) is given by

$$S_{avg} = \frac{\int_V S(R,Z)\cdot RdRdZ}{\int_V RdRdZ} = S_{\max}\cdot\frac{\int_{R_1}^{R_2} r(R)\cdot RdR}{\int_{R_1}^{R_2} RdR}\cdot\frac{\int_{Z_1}^{Z_2} z(Z)\cdot dZ}{\int_{Z_1}^{Z_2} dZ}$$

where the last equality follows if the star density distribution S(R, Z) can be factored as S_{max} · r(R) · z(Z). Specializing to the case where $S(R,Z) = S_{\max}\cdot e^{-a(R-R_1)}\cdot e^{-b(Z-Z_1)}$, gives

$$I_R \equiv \frac{\int_{R_1}^{R_2} e^{-a(R-R_1)}\cdot RdR}{\int_{R_1}^{R_2} RdR} = \frac{2\left[(1+aR_1)-(1+aR_2)e^{-a(R_2-R_1)}\right]}{a^2(R_2^2-R_1^2)}$$

and

$$I_Z \equiv \frac{\int_{Z_1}^{Z_2} e^{-b(Z-Z_1)}\cdot dZ}{\int_{Z_1}^{Z_2} dZ} = \frac{\left[1-e^{-b(Z_2-Z_1)}\right]}{b(Z_2-Z_1)}$$

with

$$S_{avg} = S_{\max}\cdot I_R\cdot I_Z$$

It is also possible to express the upper limits on the integrals as a fixed fraction, f, of the maximum star density, rather than a fixed radius. In this case, R_2 and Z_2 are defined through the following relations

$$S(R_2,Z_1) = f\cdot S_{\max} \Rightarrow R_2 = R_1 - \frac{\ln f}{a}$$
$$S(R_1,Z_2) = f\cdot S_{\max} \Rightarrow Z_2 = Z_1 - \frac{\ln f}{b}$$

in analogy with what was done for the "standard" beam dump case discussed in TM-1815. Then the integrals can be rewritten as

$$I_R \equiv \frac{2\left[(aR_1+1)(1-f)+f\ln f\right]}{\left[(\ln f)^2-2aR_1\ln f\right]} \qquad \text{(eq. A.1)}$$

$$I_Z \equiv \frac{f-1}{\ln f} \qquad \text{(eq. A.2)}$$

They are plotted in figure A.1, along with their product. I_R is plotted for the NUMI tunnel case with R=330 cm and a=0.0307 cm^{-1}. These expressions can be used to compute the ratio of the average star density to the maximum star density for any desired value of a, R_1, and f, assuming only that the star density distribution can be factored into exponentials in R and Z.

With R_1=0 and f=0.01 equations A.1 and A.2 reproduce the results in TM-1815, i.e.

$$S_{avg} = S_{\max} \cdot (0.089) \cdot (0.215) = S_{\max} \cdot 0.019$$

Unlike the beam dump case, the star density distribution in the rock surrounding the NUMI tunnel is more or less constant along the beam direction (see figure 4 in the main text). It does decrease exponentially in the radial direction, with a radial attenuation length that is approximately constant with Z (see figure A.2). Assuming a star density that is independent of Z gives I_Z=1. Taking a=0.0307 cm^{-1}, R_1=330 cm (the tunnel radius), and f=0.01 gives

$$S_{avg} = S_{\max} \cdot (0.192) \cdot (1)$$

It is useful to compare this with the value of S_{avg}/S_{max} from simply averaging the CASIM results outside the NUMI tunnel. Figure A.2 shows that the star density drops off radially to 1% of its maximum in a distance of about 150 cm (R=480 cm). The star density distribution from the CASIM calculation, averaged over the range 330 cm < R < 480 cm and 0 cm < Z < 78400 cm gives S_{avg} = 1.57x10^{-11} cm^{-3} $proton^{-1}$. S_{max} is 1.11x10^{-10}, giving a ratio of 0.141 for S_{avg}/S_{max}. This somewhat smaller value than 0.192 is due to averaging over a CASIM star density distribution in Z that is not actually a constant.

Summary

The averaging procedure used in TM-1815 leading to the factor 0.019 in the standard expression for the radionuclide concentration in ground water should be modified for the case of an extended source like the NUMI tunnel. Because of the nearly constant star density as a function of Z for fixed R, there is very little reduction to be gained in the calculated concentration due to averaging along the beam direction (I_Z~1). This is in contrast to the beam dump geometry discussed in TM-1815 where I_Z equals 0.215. To the extent that the star density does vary with Z over the length of the tunnel (by roughly a factor of two or so), it still makes little sense to average over such a large distance (~ 800 meters). The reduction factor due to radial averaging is also not as great for the tunnel geometry as for the beam dump geometry, due to the non-zero tunnel radius (I_R of 0.192 for the tunnel vs. 0.089 for the beam dump, when averaged out to the point where f=0.01).

These considerations lead to the conclusion that it may be more appropriate to take $S_{avg}=0.192 * S_{max}$. If this is done, then the limiting value of S_{max} for $3.7x10^{20}$ protons per year becomes $7.8x10^{-12}$ stars cm^{-3} $proton^{-1}$. This would require more shielding that what is discussed in the main text (roughly three more feet of concrete or one more foot of steel radially).

Implicit in this discussion is that it is reasonable to average the star density at least out to 150 cm into the dolomite rock to determine the concentration in the ground water. Also it is useful to remember that no credit has been taken for the flow of water into the tunnel. If a convincing argument can be made that water out to 75 cm in the dolomite actually flows into the tunnel, then the shielding design as described in the main text would still be adequate.

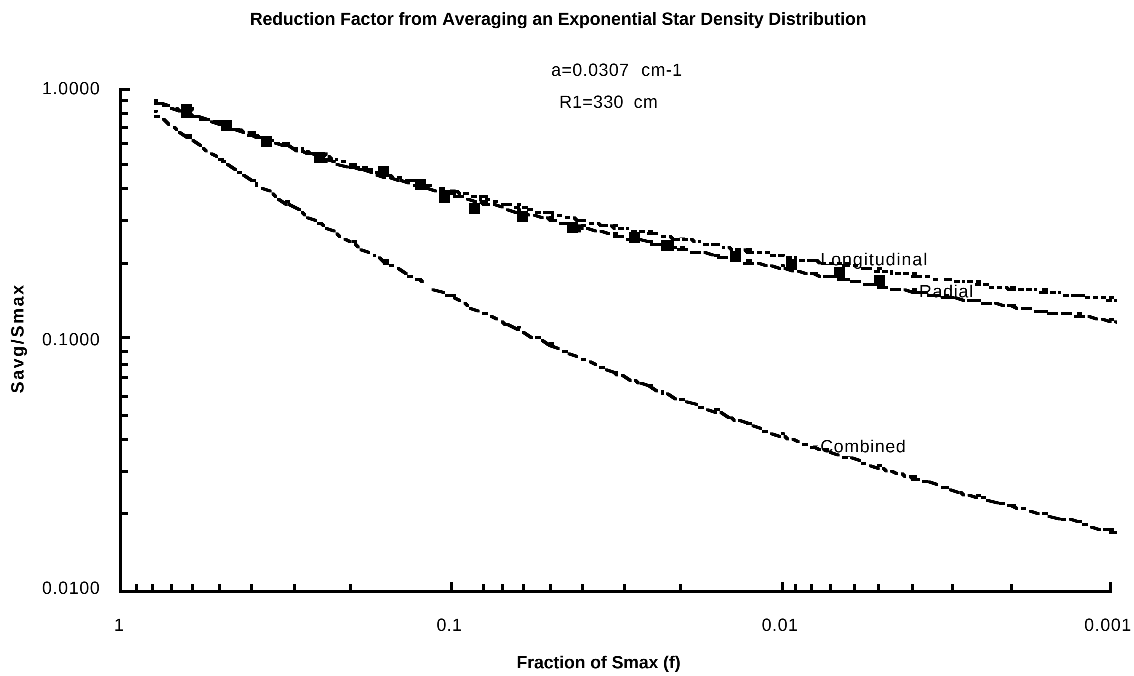

Figure A.1 - Reduction factors relating S_{avg} to S_{max} from averaging an exponentially decreasing star density distribution over radius (Radial) and distance along the beam direction (Longitudinal) and the product of the two (Combined). The radial curve assumes a tunnel radius of 330 cm and a radial attenuation length for the star density of 32.57 cm. The solid squares are from the CASIM results for a single Z bin (240 m. < Z < 256 m.) and should lie on the curve labeled "Radial" if the CASIM results are well described by an exponential in R.

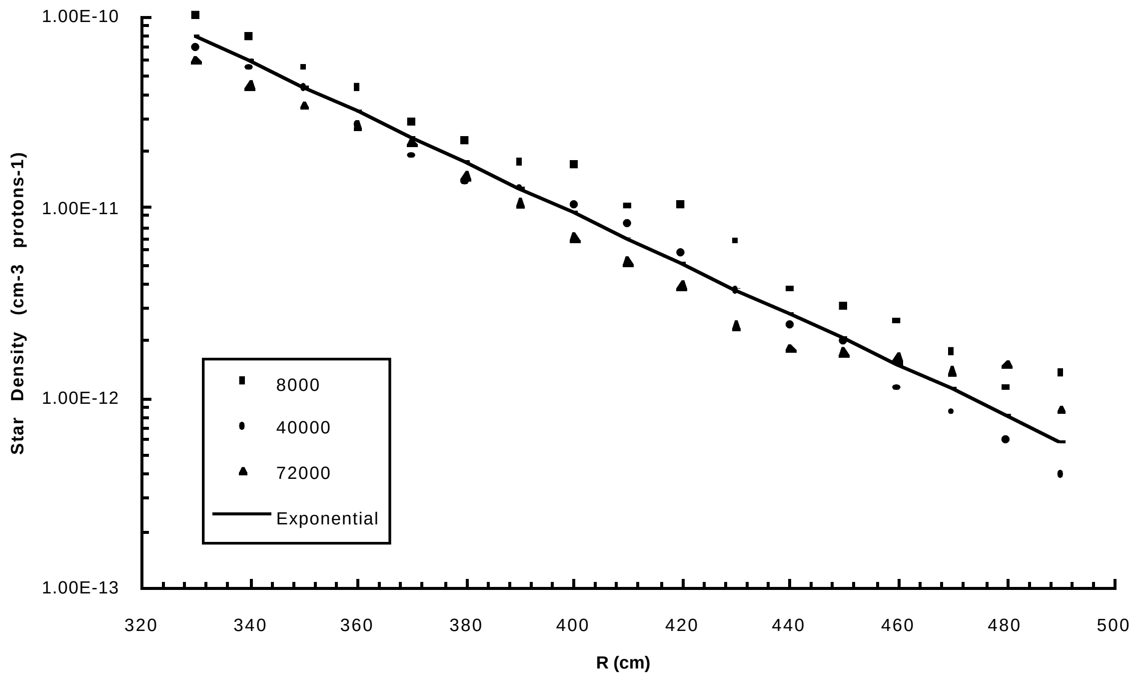

Figure A.2 - Radial dependence of the star density for several Z bins, calculated using CASIM for the shielding configuration discussed in the main text. The solid line labeled "Exponential" has an attenuation length of 33 cm and is provided for comparison to the CASIM results.